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The Wagner Turbidimeter for Measuring the Fineness of Cement.

THE inadequacy of sieves for measuring the fineness of cement has long been recognised. Several methods have been developed for the determination of sub-sieve particle sizes and the specific surface of cements. The method developed by L. A. Wagner has found widespread favour in the United States, and a description of the apparatus and the mathematical derivation of the formulæ used are fully detailed in "A Rapid Method for the Determination of Specific Surface of Portland Cement," by L. A. Wagner (*A.S.T.M. Proceedings*, Vol. 33 (1933), Part II, p. 553).

The apparatus, which is essentially a turbidimeter, consists of a source of light of constant intensity which passes through a suspension of the cement in kerosene and then into a photoelectric cell. The current generated in the cell is measured with a microammeter and the readings afford a measure of the turbidity of the suspension from which the surface area of the suspended particles is calculated. Particle size distribution is obtained by observing changes in turbidity as the particles settle from suspension.

The source of light is a six-candle-power electric lamp operated by a six-volt storage battery. A parabolic reflector is mounted behind the lamp and is focused so that a beam of approximately parallel light passes through the glass settling tank, which contains a suspension of cement particles in kerosene. There are rheostats which serve to regulate the light to the desired intensity. A water cell placed in the path of the light-beam absorbs the larger part of its radiant heat. The portion of the beam which is transmitted through the tank passes into a photoelectric cell. The current generated in the photoelectric cell is measured with a microammeter and the reading indicated affords a measure of the turbidity of the suspension.

The lamp, water cell, and photoelectric cell are mounted on a shelf which is raised or lowered by two lead screws to bring the level of the light to any desired depth of the suspension in the settling tank. A pointer and scale on the outside of the cabinet indicate the position of the shelf.

The function of the movable shelf is to shorten the time required to obtain the sedimentation curve of a suspension. Turbidity readings of the larger particles, which fall out rapidly, are obtained at the lowest level of the suspension. Rather than wait for the smaller particles to settle to this level, which would require several hours, the shelf is raised so that the light-beam is directed through lesser depths of the suspension. The levels at which the readings are made are selected so that about one minute elapses between readings for particle diameter intervals of five microns. This gives the operator ample time to observe and record the microammeter reading and to move the shelf into position for the next reading.

The sample to be tested is dispersed in kerosene, to which a few drops of oleic acid have been added, by stirring in a test tube with a rotating brush. The mixture is then transferred to the settling tank and kerosene is added to bring the suspension to the desired volume. The tank is agitated to distribute the particles uniformly, and is placed in the path of the light-beam. Microammeter readings are then observed at the proper depths and time intervals calculated from Stokes's law to correspond to particle diameters of 60, 55, 50, 45, 40, 35, 30, 25, 20, 15, 10, and 7·5 microns.

Readings giving the distribution down to 7·5 microns are obtained in about ten minutes, which is the time required for all particles larger than 7·5 microns to settle below the level of the light-beam with this particular apparatus and suspending liquid. A complete determination on an unknown sample, including the calculating of results, requires about half an hour.

The calibration of the apparatus is made by adjustment of the full light intensity until the determination of the specific surface of the United States National Bureau of Standards sample agrees with its assigned value within $\pm$ 15 square centimetres per gramme. If a specific surface greater than the assigned value is obtained, the light intensity should be increased and the analysis repeated. If a specific surface less than the assigned value is obtained, the light intensity should be decreased and the analysis repeated. When the correct intensity has been ascertained, the intensity through the retarding filter, which can be swung into the light-beam and through the tank filled with clear kerosene, is recorded and this becomes the permanent reference value for the intensity of light. The rheostats can then be adjusted at the beginning of each test to give this value through the filter plus tank of clear kerosene from the regular supply.

The following experimental work by G. Molinari and A. Mendes on the regulation of the instrument, reproducibility of results, and possible causes of error in the method appears in Bulletin No. 21 of the Instituto de Pesquisas Tecnologicas de S. Paulo, published in February, 1939.

Regulation of the Turbidimeter.

The regulating method indicated in the instructions has two great disadvantages: it is very elaborate owing to the large number of tentative attempts to be made, and it requires a standard sample of Portland cement subject to modification in accordance with the weather, so that its specific area rarely remains constant. With the object of eliminating these difficulties the authors have adopted a method which does not require standard samples in the tentative tests, but which is based on the theory of the apparatus.

As the intensity of the light passing through the clean kerosene is to be $I_0 = 100$ micro-amperes, and this reading cannot be obtained on the microammeter because the scale only reads up to 50 micro-amperes, a shunt (*r*), as shown on the sketch of the apparatus (*Fig.* 1), was used. The shunt resistance

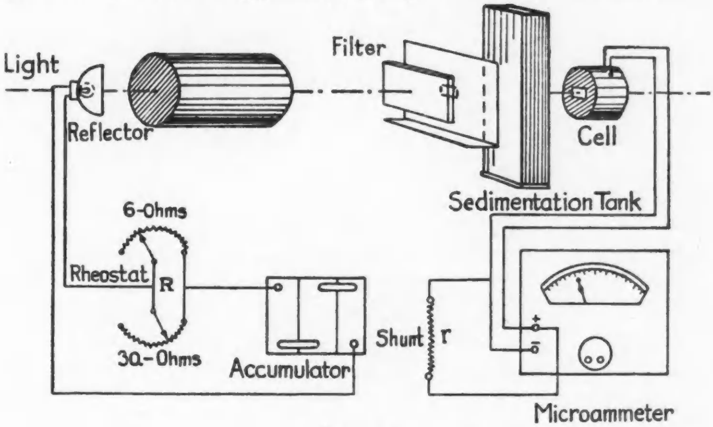


Fig. 1.

is the same as the resistance of the microammeter, so that the readings on this apparatus would correspond to half the intensity of the current generated by the cell.

The regulation is very simple and is as follows. (1) Connect the shunt to the microammeter and place the container of clean kerosene in the path of the light without the filter; (2) Connect the lamp and regulate the light intensity through the rheostat (R) so that the reading on the microammeter will be 50 micro-amperes. This is equivalent to fixing the intensity of the light through the clean kerosene at $I_0 = 100$ micro-amperes[1]; (3) Place the filter in the path of the light and withdraw the shunt. The new reading on the microammeter (I_2) will be used for the ordinary regulation of the turbidimeter; (4) Withdrawing the kerosene container, the reading I_1 of the light intensity through the filter is obtained, and this can also be used for the regulation of the turbidimeter.

(1) I_0 = Intensity of the current generated by the cell for the light just passing through the clean kerosene.
I_1 = Ditto for the light just passing through the filter.
I_2 = Ditto for the light passing through the filter and the clean kerosene.

TABLE I.

REGULATION OF THE TURBIDIMETER.

Standard Sample No. 114. $r = 87 \cdot 7\%$. $S = 1{,}900$ cm²/g.

d	Readings (Id)			
	First Test	Second Test	Third Test	Fourth Test
60	19·0	18·8	18·2	18·9
55	19·2	18·9	18·3	19·0
50	19·5	19·1	18·5	19·3
45	19·7	19·5	18·8	19·5
40	19·9	19·7	19·2	19·9
35	20·4	20·2	19·6	20·3
30	21·0	20·8	20·1	20·8
25	21·8	21·6	21·3	21·7
20	23·0	22·6	22·3	23·1
15	24·8	25·4	24·3	25·0
10	28·0	28·0	27·5	28·4
7·5	30·8	30·5	30·0	30·8
Initial	15·4	15·4	15·4	15·4
Final[1]	15·4	15·4	15·4	15·4

[1] Intensity of the light going through the filter, before and after the test.

d	Logarithms (log Id)			
60	1·279	1·274	1·260	1·276
7·5	1·489	1·484	1·477	1·489
55	1·283	1·276	1·262	1·279
50	1·290	1·281	1·267	1·286
45	1·294	1·290	1·274	1·290
40	1·299	1·294	1·283	1·299
35	1·310	1·305	1·292	1·308
30	1·322	1·318	1·303	1·318
25	1·338	1·334	1·328	1·336
20	1·362	1·354	1·348	1·364
15	1·394	1·405	1·386	1·398
10	1·447	1·447	1·439	1·453
First term of the denominator..	1·500	1·500	1·500	1·500
0·75, log $I_{7\cdot5}$ ..	1·117	1·113	1·108	1·117
(*)	15·956	15·917	15·790	15·948
−11·5, log I_{60} ..	−14·706	−14·653	−14·491	−14·680
Denominator ..	1·250	1·264	1·299	1·268
Numerator ..	2·403	2·419	2·466	2·411
S = cm²/g. ..	1·922	1·914	1·898	1·901

(*) Sum of the positive terms of the denominator.

The exactness of this regulating process, which consists of a single adjustment of the light intensity, by checked as follows. (1) The value of I_1 is established by this process in the apparatus and we find that $I_1 = 24$ micro-amperes, which

corresponds exactly to the value previously obtained using the standard sample ; (2) The photo-electric cell was superseded by another cell, necessitating fresh regulation of the apparatus. The new value of I_1 was fixed by this method and it was found that $I_1 = 15{\cdot}4$ micro-amperes. With this value the specific area of the standard sample was calculated and this confirmed the exactness of the new method.

In *Table* I are reproduced some of the results of this confirmation. The arrangement of this table is very convenient for the application of the formula

$$S = \frac{38\, r\, (2 - \log I_{60})}{1{\cdot}5 + 0{\cdot}75 \log I_{7\cdot5} + \log I_{10} + \ldots + \log I_{55} - 11{\cdot}5 \log I_{60}} \quad \text{(X)}$$

where S = specific surface in cm.^{2} per gramme, and

r = percentage passing the No. 325 sieve in per cent.

The relation between the current generated by the cell and the luminous intensity is more exact when the electric resistance of the respective circuit is smaller.(1) With the Weston Photronic cell and the low resistance (100 ohms) microammeter used it is possible to determine the relation between those elements in accordance with the assumptions of the method used to determine the specific area through the turbidimeter. The increase of the luminous intensity of the current from the return of the filter cannot alter the characteristics of the cell as a result of a phenomenon of fatigue.(2) According to Zworykin and Wilson, the Weston Photronic cells do not suffer as a result of strong luminous intensities, and the same applies when they are in short circuit.(3) For the purpose of verifying this assertion we carried out several experiments with a cell (594 model, No. 69765-18). The results (see *Table* Ia) show that no appreciable fatigue takes place when the cell is exposed to a luminous intensity of 100 micro-amperes, and the same applies if the exposition is extended longer than is necessary for the regulation.

In *Table* Ia we have

T = duration in minutes of the exposure to a luminous intensity corresponding to a current of 100 micro-amperes generated by the cell ;

I_1 = readings in micro-amperes, obtained without the shunt, with interposition of the filter ;

I_0 = readings in micro-amperes obtained with the shunt at the beginning and at the end of the exposure, with the light going through the clean kerosene only.

Reproducibility of the Results.

In order to determine the degree of reproducibility of the results obtained for the establishment of the specific area of the same cement, the Institute carried out experiments following two different systems : (*a*) determination of reproducibility in the tests carried out in the Institute, and (*b*) determination of reproducibility in tests carried out, using the same sample, in the Institute and in other laboratories in Brazil.

(1) and (3) Zworykin and Wilson, Photocells and Their Application.
(2) L. A. Wagner, *A.S.T.M.*, Vol. 33, Part II, 1933, p. 569.

TABLE Ia.

T	2	4	6	8	10	16
I_1 Initial	16·0	16·0	16·0	16·0	16·10	16·15
I_1 Final	16·0	16·0	16·0	16·0	16·15	16·10
I'_0 Initial	50·0	50·0	50·0	50·0	49·95	49·70
I'_0 Final	50·0	50·0	50·0	50·0	49·50	49·20

REMARKS.—The small variations observed, which otherwise are negligible for the purpose we have in mind, can perhaps be attributed to the influence of the temperature in the accumulator, in the shunt or in the microammeter.

(*a*) REPRODUCIBILITY TESTS IN THE INSTITUTE.—From the year 1937 the Institute has been using the turbidimeter, and the following is a brief summary of the main results obtained in the study of the reproducibility of the results. On *Table* II are listed 20 different samples of Brazilian cements ; five tests were made on each sample. On the basis of these values the conclusion is reached

TABLE II.

SPECIFIC AREA (cm^2/g.).

Samples	Tests					Averages	Variation Coefficient (%)	Maximum Divergence, %	
	1	2	3	4	5			Of the Average	Between Two Tests
1	1,808	1,915	1,816	1,746	1,822	1,821	3·1	4·1	9·2
2	1,838	1,864	1,865	1,873	1,878	1,863	0·7	1·3	2·3
3	2,352	2,476	2,496	2,400	2,432	2,431	2·1	3·2	5·9
4	2,482	2,458	2,478	2,405	2,422	2,449	1·2	1·8	3·1
5	2,099	2,259	2,124	2,149	2,165	2,160	2·5	4·6	7·3
6	2,158	2,154	2,102	2,225	2,103	2,148	2·1	3·6	5·7
7	1,740	1,735	1,677	1,620	1,703	1,695	2·6	4·4	7·1
8	2,079	2,169	2,048	2,015	2,078	2,077	2·5	4·4	7·4
9	1,769	1,703	1,741	1,702	1,936	1,710	2·4	4·3	7·8
10	1,627	1,738	1,572	1,616	1,626	1,636	3·4	3·9	6·0
11	1,498	1,489	1,469	1,687	1,473	1,523	5·4	10·8	13·8
12	1,714	1,618	1,600	1,640	1,670	1,648	2·4	4·0	6·9
13	1,647	1,641	1,665	1,646	1,647	1,649	0·3	10·9	1·5
14	2,383	2,322	2,308	2,163	2,303	2,296	3·1	5·8	9·7
15	1,590	1,610	1,595	1,577	1,554	1,583	1·3	1·9	3·5
16	1,640	1,629	1,585	1,555	1,614	1,605	1·9	2·5	5·3
17	1,540	1,486	1,441	1,482	1,375	1,464	2·6	6·1	11·3
18	1,631	1,610	1,650	1,646	1,572	1,621	1·8	3·0	4·8
19	1,729	1,746	1,748	1,753	1,750	1,745	0·5	0·9	1·4
20	1,698	1,660	1,740	1,729	1,660	1,697	2·0	2·5	4·8
Averages							2·2	3·7	6·24

that the maximum divergence between two tests carried out by the same operator amounts, on an average, to 6 per cent., and may be as high as 14 per cent. The coefficient of variation, the quotient of the standard deviation $\sqrt{\frac{\Sigma d^2}{N}}$ by the arithmetical average, amounts on an average to 2·2 per cent.

Table III shows the residues on screen No. 325 of the same 20 samples listed in *Table* II, of which five tests of each were made, with the object of giving an idea of the importance of the divergence to be found between two tests carried out by the same operator. As the result of this series of tests the conclusion

TABLE III.

RESIDUE ON SIEVE NO. 325 (%).

Samples	Test Results					Averages	Coefficient of Variation, (%)	Divergence between Two Test Results
	1	2	3	4	5			
1	16·5	16·2	15·0	16·5	16·5	16·14	3·45	1·5
2	16·7	15·4	15·0	16·6	16·6	16·06	4·45	1·7
3	5·0	5·1	5·0	5·3	5·8	5·24	5·74	0·8
4	5·4	5·0	5·1	5·6	5·3	5·28	5·67	0·6
5	6·4	6·5	6·0	7·5	6·4	6·56	7·53	1·5
6	6·3	6·5	7·5	6·2	6·9	6·68	7·64	1·3
7	14·0	13·5	14·2	14·0	14·0	13·94	1·67	0·7
8	8·4	7·7	9·0	8·6	7·6	8·26	6·49	1·3
9	16·3	17·1	17·0	17·4	16·9	16·94	2·13	1·1
10	19·0	18·5	19·8	19·3	19·2	19·16	2·21	1·3
11	16·1	17·2	16·9	16·8	16·2	16·64	2·53	1·1
12	16·0	16·8	16·7	17·8	17·3	16·92	3·56	1·8
13	14·8	15·9	15·7	15·7	15·7	15·56	2·49	1·1
14	5·8	5·2	5·0	6·6	5·6	5·64	8·70	1·6
15	14·0	14·8	14·3	15·1	14·6	14·56	2·63	1·1
16	12·7	11·7	11·9	13·5	14·5	12·86	8·07	2·8
17	17·9	18·6	18·4	17·4	15·9	17·64	3·73	2·7
18	14·1	14·5	14·4	14·1	14·5	14·32	1·28	0·4
19	15·0	14·1	15·3	14·5	13·2	14·42	5·10	1·8
20	12·0	12·2	13·3	12·8	11·7	12·40	4·65	1·6
Averages	..	..	..	..	..	.. ..	4·49	1·39

was reached that the maximum divergence between two tests carried out with the same sample amounts, on an average, to 1·4 per cent., failing to reach 3 per cent. of the screened material. This error does not greatly influence the value of the specific area. The coefficient of variation of these test results amounted on an average to 4·5 per cent. It may be advisable to point out that the specific area is roughly proportional to the material passing through the screen and not to the material retained on the screen, and in consequence the coefficients of variation corresponding to the specific area and to the residues respectively do not permit direct comparison.

Table IV gives particulars of a series of tests with ten different brands of cement ; two tests were made with each sample. In this case the differences are of the same order as those in *Table* III.

TABLE IV.

TESTS OF 10 SAMPLES OF DIFFERENT BRANDS.

Tests	Cement Brand	Material retained on Sieve No. 325 (%)	Specific Area. S = cm²/g.			Divergence from the Average, (%)
			First Test Results	Second Test Results	Average	
1	A	22·4	1,305	1,389	1,342	2·8
2	B	18·0	1,724	1,764	1,744	1·1
3	C	18·8	1,560	1,614	1,587	1·7
4	D	15·5	1,676	1,645	1,660	0·9
5	E	7·3	1,754	1,710	1,732	1·3
6	F	12·3	1,838	1,790	1,814	1·3
7	G	18·8	1,620	1,680	1,650	1·8
8	H	13·5	1,532	1,528	1,530	0·1
9	I	10·0	1,813	1,705	1,759	3·1
10	J	12·0	1,785	1,809	1,797	0·7

In order to confirm these conclusions, ten tests were made on the same sample by a single operator (*Table* V). The values corresponding to the transmittances are indicated.

TABLE V.

SAMPLE " X."

Tests	Residue on Sieve No. 325 (%)	Specific Area, cm²/g	Transmittance cm²
1	16·5	1,808	738
2	16·2	1,915	771
3	15·0	1,816	743
4	16·5	1,746	736
5	16·5	1,822	804
6	16·7	1,838	716
7	15·4	1,864	751
8	15·0	1,865	722
9	16·6	1,873	721
10	16·6	1,878	726
Averages ..	16·1	1,842	743

The divergences of the values of the specific area in *Table* V are as follows :

Divergence of the Specific Area Values : Per cent.

Maximum divergence from the average (4th test results) .. 5·2

Maximum divergence between two test results (2nd and 4th) .. 9·2

Coefficient of variation .. .. 2·4

Disregarding the 2nd and 4th test results :

Average = 1,845 square cm./g. Per cent.

Maximum divergence from the average (1st test results) .. 2·0

Maximum divergence between two test results (1st and 10th) .. 3·8

Coefficient of variation .. .. 1·4

On *Table* VI are given the results obtained in another series of ten tests on a finely-ground sample. The values obtained for the transmittance " c " are also indicated.

TABLE VI.
SAMPLE " Y."

Tests	Residue on Sieve No. 325 (%)	Specific Area, cm^2/g	Transmittance, cm^2
1	5·0	2,352	760
2	5·1	2,476	749
3	5·0	2,496	752
4	5·3	2,400	751
5	5·8	2,432	749
6	5·4	2,482	736
7	5·0	2,458	759
8	5·1	2,478	759
9	5·6	2,405	769
10	5·3	2,422	733
Averages ..	5·3	2,440	752

Divergence of the Specific Area Values: Per cent.
Maximum divergence from the average (1st test results) .. 3·6
Maximum divergence between two test results (1st and 3rd) .. 5·9
Coefficient of variation .. .. 1·8

Disregarding the 1st test results:
Average = 2,450 square cm./g. Per cent.
Maximum divergence from the average (4th test results) .. 2·0
Maximum divergence between two test results (3rd and 4th) .. 3·9
Coefficient of variation .. .. 1·4

TABLE VII.
SAMPLE 1-E.S.E. SPECIFIC AREA ($cm^2/g.$).

Laboratories	Test Results					Averages	Coefficient of Variation, (%)	Maximum Divergence (%)	
	1	2	3	4	5			From the Average	Between Two Test Results
I.P.T. ..	1,640	1,629	1,585	1,555	1,614	1,605	1·9	3·1	5·3
Perús ..	1,662	1,694	1,666	1,669	1,702	1,679	1·0	1·4	2·4
Mauá ..	1,570	1,585	1,640	1,593	1,625	1,603	1·6	2·3	4·4

The maximum divergence between the average results of two laboratories is 4·6 per cent., and the coefficient of variation of these results is 2·2 per cent.

(*b*) REPRODUCIBILITY IN CO-OPERATIVE TESTS.—In order to ascertain the degree of uniformity which could be obtained in tests with the same sample, the

Institute organised a programme of tests by several laboratories. The results from the Companhia Brasileira de Cimento Portland (São Paulo) and the Companhia Nacional de Cimento Portland (Rio de Janeiro) have been received.

TABLE VIII.

SAMPLE 1-E.S.E. RESIDUE ON SIEVE NO. 325 (%).

Laboratories	Test Results					Averages	Coefficient of Variation (%)	Maximum Divergence between Two Test Results
	1	2	3	4	5			
I.P.T. ..	12·7	11·7	11·9	13·5	14·5	12·9	8·1	2·8
Perús ..	16·0	15·0	15·3	16·0	14·7	15·4	3·4	1·3
Mauá ..	14·0	14·3	13·9	13·9	13·9	14·0	1·1	0·4

The maximum divergence between two laboratories is 2·5 per cent., and the coefficient of variation is 7·2 per cent.

TABLE IX.

SAMPLE 2-E.S.E. SPECIFIC AREA ($cm^2/g.$).

Laboratories	Test Results					Averages	Coefficient of Variation (%)	Maximum Divergence (%)	
	1	2	3	4	5			From the Average	Between Two Test Results
I.P.T. ..	2,320	2,372	2,280	2,350	2,375	2,343	1·5	2·7	4·1
Perús ..	2,359	2,386	2,372	2,331	2,368	2,363	0·8	1·4	2·3
Mauá ..	2,280	2,290	2,250	2,270	2,265	2,271	0·6	0·9	2·2

The maximum divergence between the average results of two laboratories is 4·0 per cent., and the coefficient of variation of these results is 1·7 per cent.

TABLE X.

SAMPLE 2-E.S.E. RESIDUE ON SIEVE NO. 325 (%).

Laboratories	Test Results					Averages	Coefficient of Variation (%)	Maximum Divergence between Two Test Results
	1	2	3	4	5			
I.P.T. ..	5·7	5·0	6·1	6·2	5·4	5·7	7·8	1·2
Perús ..	7·8	6·5	6·5	7·6	6·9	7·1	7·4	1·3
Mauá ..	7·0	7·0	6·6	6·8	6·9	6·9	2·2	0·4

The maximum divergence between the average results of two laboratories is 1·4 per cent., and the coefficient of variation of these results is 9·3 per cent.

For each series of tests the Institute sent to those laboratories a dated and sealed air-tight flask containing 75 grammes of cement from a sample which had been carefully homogenised. With these samples each laboratory carried out five tests of the specific area, giving the corresponding value to the residue left on sieve No. 325. *Tables* VII to X give summaries of the results.

For the purpose of confirmation, *Table* XI comprises the results obtained in tests by different laboratories in the United States (see *A.S.T.M.*, Vol. 34, Part II, p. 312). In the United States tests the divergence between two test

TABLE XI.

SPECIFIC AREA, IN cm^2/g.

Tests		University of California	Bureau of Standards	Bureau of Reclamation	Averages	Coefficient of Variation	Maximum Divergence (%)	
							From the Average	Between Two Test Results
1	L-5	1,261	1,380	1,435	1,359	4·7	7·2	12·2
2	L-6	1,328	1,400	1,400	1,376	2·5	3·5	5·3
3	L-7	1,325	1,460	1,455	1,413	4·2	6·2	9·7
4	L-9	1,222	1,470	1,400	1,364	7·6	10·4	18·6
5	L-12	1,248	1,320	1,275	1,281	2·3	3·0	5·6
6	L-4 (1,000)	1,073	1,200	1,060	1,111	5·7	8·0	12·4
7	L-4-2 (1,200)	1,360	1,480	1,305	1,382	5·3	7·1	12·6
8	L-4 (1,400)	1,486	1,580	1,640	1,569	3·5	5·3	9·9
9	L-4 (1,600)	1,808	1,910	1,780	1,833	3·0	4·2	7·0
10	L-13 (1,000)	1,042	1,130	1,075	1,082	3·4	4·4	8·1
11	L-13-2 (1,200)	1,349	1,450	1,360	1,386	3·3	4·6	7·2
12	L-13 (1,400)	1,522	1,630	1,630	1,594	3·2	4·5	9·0
13	L-13 (1,600)	1,719	1,840	1,840	1,800	3·2	4·5	6·8
14	L-20 (1,000)	984	1,140	1,130	1,084	6·6	9·2	15·5
15	L-20 (1,200)	1,295	1,350	1,370	1,338	2·4	3·2	5·6
16	L-20 (1,400)	1,603	1,640	1,665	1,636	1·6	2·0	3·8
17	L-20 (1,600)	1,762	1,830	1,920	1,834	8·5	4·7	8·6
Averages ..	.. ..	..	..	.. ..	..	3·9	5·4	9·2

results is considerably greater than that indicated in the previous tables. On average it amounts to 9·2 per cent., having reached 18·6 per cent. The coefficient of variation is, on average, 3·9 per cent.

(*To be concluded.*)

"Low-Heat" Cement in Practice.

THEIR opinion of the advantages and limitations of "low-heat" cement as the result of the use of 5,000,000 barrels of this type of cement in the United States is given by Messrs. H. S. Meissner and W. T. Moran, of the United States Bureau of Reclamation, in a recent issue of *Engineering News-Record* (November 10, 1938). After describing the chemical composition of "low-heat" cement, the authors state:

The use and limitations of low-heat cement should be understood before employing it, and its adaptation for a particular job should be determined considering the structural design, construction schedule and thermal properties of the concrete, and conditions as a whole. Low early strength during the winter season may under some conditions need construction procedure, such as form removal, which differ from the ordinary. Since strength development is not so rapid as with other types of cements, a longer curing period is desirable. The strength of mass concrete made with low-heat cement will at later ages equal if not exceed that of standard cement concrete. The permeability of concrete made with low-heat cement has been shown by some laboratory tests to be slightly less than that containing standard cement. Recent laboratory studies corroborate field observations that low-heat cement concrete possesses superior resistance to cracking. It is concluded, therefore, that low-heat cement concrete is better able, through favourable plastic flow or extensibility characteristics, to adjust itself to temperature strains occurring during its early history, and is for this reason better adapted for use in mass concrete.

Modified cement was evolved from the research and experiences with low-heat in an effort to improve or "modify" standard cement where it is considered most deficient. Modified cements differ, in general, from low-heat cement in that the C_3S content or lime : silica ratio is higher. Modified cements have some of the more desirable characteristics of low-heat cement while retaining initial strengths equal to the standard product. Modified cement is now fast replacing standard cement in construction work undertaken by the Bureau of Reclamation, and has been used on several mass concrete works.

In cases where resort is not had to artificial cooling, final internal concrete temperatures may be as high with low-heat cement as with modified cement, due to the fact that the latter has a greater early rate of heat production, and therefore a greater proportion of heat is lost from the concrete before it is covered by a succeeding lift. Low-heat cement, on the other hand, possesses decided advantage in connection with artificial cooling, this combination permitting internal temperatures to be reduced. For the construction of the low Grand Coulee dam modified cement was employed, even though the concrete was cooled, as it was concluded that an advantage already existed in that about 10 deg. lower average initial concrete temperatures would be secured. Compared with low-heat cement, modified cement has, however, not been as successful in reducing temperature cracks, although it is observed to be an improvement over standard cement.

Experience in Dam Construction.

Low-heat cement was first used in the construction of Morris dam in which 570,000 barrels were used. At that time considerable information was available from the uncompleted researches on cements for Boulder dam, and on the basis of this the first low-heat specifications were formulated. Reports on the experiences with this cement at Morris dam were satisfactory, and the opinion was expressed that less cracking occurred than on other similar structures. At first the cement was accepted with a fineness of 85 per cent. passing the No. 200 sieve, but this requirement was increased to 92 per cent. Recent inspection of the concrete in this dam indicates that it is in excellent condition, which is attributed to painstaking workmanship and to the type of cement used.

During the early construction work on Rodriguez dam a coarse-ground (85 per cent. passing the No. 200 sieve) standard cement was tried in an attempt to alleviate the cracking experienced with standard cement ground to 92 per cent. passing the No. 200 sieve. This did not result in any material improvement. Later 100,000 barrels of low-heat cement, identical to that being supplied for Morris dam, were used, and found very successful in overcoming cracking.

Construction of Boulder dam was started before investigations on low-heat cement were completed. Some mass concrete in the dam was therefore placed with standard Portland cement, as a result of which a direct comparison of low-heat cement under identical field conditions was possible. From experience on the job it was concluded that the use of low-heat cement resulted in concrete more free from cracks than is generally obtained with the standard cement. Where cracking did occur it was of a minor nature and to a great extent associated with shrinkage due to drying. No serious or extensive cracks have been noted in surveys regularly made every three months, and there are no cracks which continue for any considerable distance in the main body of the dam, such as have been noted in other structures.

The conclusion was also reached that concrete made with low-heat cement was more workable and required less water for the same slump, due principally to increased fineness. Since laboratory data and field experience had shown that low-heat cement acquired strength slowly in concrete cast with low initial temperature, it was considered desirable to blend low-heat cement with normal cement (in the proportions of 6 parts low-heat cement to 4 parts normal cement) during the winter months, in order to expedite removal of formwork and to ensure more secure form anchorages in relatively green concrete. There were also other reasons, concerned with design, which prompted the use of this blend. The mean annual temperature at Boulder dam is 72 deg. F., the highest mean maximum monthly being 108 deg. F. and the lowest mean minimum monthly 39 deg. F.

Low-heat cement is also being used in the Bartlett, Parker, and Marshall Ford dams. Bartlett dam is a multiple-arch dam with hollow buttresses, in places 7 ft. thick, for which studies on heat flow and dissipation showed considerably lower resultant maximum temperatures with the use of low-heat

cement than with modified cement. Parker and Marshall Ford dams are massive structures, both in regions with hot climates where initial concrete temperatures are high. Cooling was employed at Parker dam, as at Boulder dam. Observations with low-heat and modified cements at Bartlett dam substantiate the conclusion that the former type has superior resistance to cracking.

The increased fineness required in low-heat cement, due principally to the inherently low initial strengths which are obtained, aids the early production of heat by increasing the rate of heat evolution ; this is a desirable effect inasmuch as some of the heat may then be liberated from the concrete before it is covered by the following lift. In addition to increasing early strength, increased workability, greater freedom from bleeding and reduced water requirements are also obtained with cements of relatively high fineness. A recent experience of the Bureau was the use of a relatively coarsely ground standard cement in concrete repair work at Arrowrock dam. Pronounced bleeding difficulties were experienced on the job and were remedied by increasing the fineness of the cement from about 1,450 to 2,000 sq. cm. per gr. of surface area. The same effects were experienced during the construction of Morris dam.

Manufacture of Low-Heat Cement.

The raw materials used at five of the eight plants producing low-heat cement cover a rather wide range, each plant using no less than three different materials. Limestone, high-lime, and high-silica cement rock, ferruginous shale, siliceous tuff, granite diorite, quartzite, and sandstone are used for the basic mix, while hematite or iron pyrites are used foı the iron addition at all plants with one exception. At two of the plants where pyrites was first employed, a change to hematite was made due to the high resulting SO_3 content of the clinker. The kilns used for burning the clinker ranged from units as small as 8 ft. by 100 ft. to 11 ft. by 275 ft. The output of low-heat clinker was reported by two plants to have been increased by 8 and 15 per cent. respectively ; by two other plants no increase was noted ; and by the last plant a lower output was claimed. At all plants a lower temperature of burning and reduced fuel consumption for low-heat clinker as compared with the standard was experienced, with the exception of one plant which claimed the same temperature of burning and fuel consumption. Difficulties in burning the low-heat clinker were encountered at several plants until lower burning temperatures were employed and exceptionally large clinker and kiln rings were avoided.

In grinding the clinker all plants reported a reduction in output for low-heat cement of from 10 to 40 per cent., three plants reporting a one-third reduction. In general, it was the opinion that this reduction was due both to the increased fineness requirement and to the hardness of the clinker. This increased resistance to grinding of clinker of low-heat composition is also substantiated by laboratory tests using a small ball mill. The development of the proper burning technique in some instances resulted in clinker which was less difficult to grind.

Economy of Clinker Cooling.

A CLINKER cooler which recovers 130,000 B.T.U. per barrel may, says Mr. W. R. Bendy in a recent number of *Rock Products*, save substantially more than 10 lb. of 13,000-B.T.U. coal. When the heating value of a fuel is measured in a calorimeter, the products of combustion are cooled to room temperature, but no practical rotary kiln cools its waste gases to room temperature. Therefore no kiln removes as many heat units from the combustion gases as the calorimeter says there are in the fuel. On the other hand, heat recovered in a clinker cooler may be slipped into the kiln through a " back door," combustion air has to go in any way, and it provides free admission. Heat taken in by preheating the combustion air is all at the disposal of the kiln, because it brings in its train

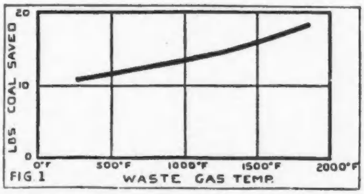


Fig. 1.—Showing the number of pounds of 13,000-B.T.U. coal saved by clinker cooler.

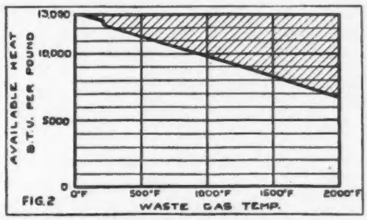


Fig. 2.—Available heat in 1 lb. of coal with relation to various gas temperatures. Shaded area represents heat lost in combustion products.

no extra products of combustion to carry away heat in the waste gases. The kiln may waste some of the heat (by radiation, for example), but that is the fault of the kiln.

The amount of heat recovered depends on the waste-gas temperature. When the heat comes from combustion, a higher waste-gas temperature means that more heat is carried out by the products of combustion, and a smaller proportion is available heat. The heat which gains free admission with the combustion air is all available heat, regardless of the waste-gas temperature.

With 13,000-B.T.U. coal, the fuel saved by recovering 130,000 B.T.U. is shown in *Table* 1:

TABLE 1

Waste-gas Temperature	Lb. of Coal saved
70 deg. F.	10·0
500 deg. F.	11·5
1,000 deg. F.	13·2
1,500 deg. F.	15·7

Fig. 1 shows the increasing rate of heat recovery with higher waste-gas temperatures. The higher the waste-gas temperature, the greater is the advantage in recovering heat from the clinker. Hence clinker coolers are more profitable on dry-process kilns than on wet-process kilns. Consider an ordinary West Virginia kiln coal of the following analyses:

TABLE 2

AVAILABLE HEAT PER POUND OF COAL AS FIRED

Waste-gas Temperature	Heat in Combustion Products, B.T.U.	Heat in Coal, B.T.U.	Available Heat, B.T.U.
70 deg. F.	—	13,000	13,000
500 deg. F.	1,667	13,000	11,333
1,000 deg. F.	3,150	13,000	9,850
1,500 deg. F.	4,695	13,000	8,305

APPROXIMATE ANALYSIS

AS FIRED

Moisture	1·6
V.C.M.	35·7
F.C.	53·2
Ash..	9·5
Total	100·0

ULTIMATE ANALYSIS

AS FIRED

Hydrogen	4·8
Carbon	75·1
Nitrogen	1·3
Oxygen	5·8
Sulphur	1·9
Moisture	1·6
Ash	9·5
Total	100·0

Heating value: 13,000 B.T.U.

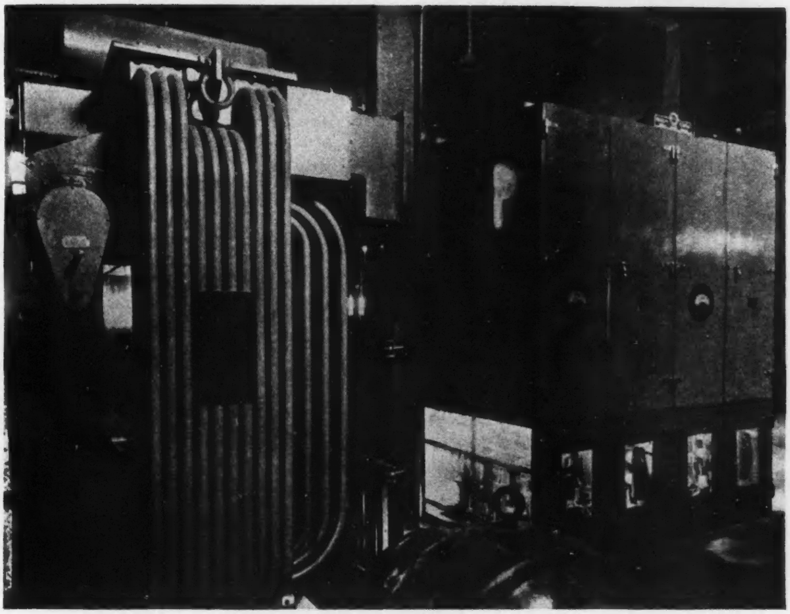
One pound of this coal requires 10·142 lb. of air for perfect combustion and produces: H_2O, 0·455 lb.; CO_2, 2·753 lb.; SO_2, 0·038 lb.; N_2, 7·811 lb. The heat content of these combustion products must be subtracted from the heating value of the coal to obtain the available heat which is shown in *Table* 2.

The available heat in 1 lb. of coal with relation to waste-gas temperature is illustrated in *Fig.* 2. With a waste-gas temperature of 500 deg. F., the available heat of the 13,000-B.T.U. coal is 11,333 B.T.U. per lb. Therefore, 13,000 B.T.U. of recovered heat is not the equivalent of 2 lb. of coal, but of 13,000 ÷ 11,333 = 1·15 lb. of coal. At 1,000 deg. F., the equivalent is 1·32 lb., and at 1,500 deg. F. 1·57 lb.

Switchgear Extensions at a Cement Works.

EXTENSIONS at the Vectis Works, Isle of Wight, of The Associated Portland Cement Manufacturers, Ltd., have made it necessary to install new sub-station switchgear. Power is taken from the supply company by duplicate incoming feeders at 11,000 volts, 3-phase, 50 cycles, and the switchboard is arranged to control the incoming supply and also to provide accommodation for the supply company's meters and consumer's check meters.

The switchboard consists of six units of the Crompton Parkinson draw-out truck type incorporating circuit breakers having a proved rupturing capacity of



Switchgear at a Cement Works.

150 MVA. in accordance with British Standard Specification No. 116 of 1937, this rating having been recently confirmed at a testing station. In these tests it was only necessary to change the arcing contacts once and the oil level at the end of the test was scarcely altered, while the general behaviour indicated a large factor of safety. The design of the truck unit has been considered from the point of view of the thermal capacity and short-circuit stress to ensure satisfactory operation under all conditions.

In addition to this switchboard, a single unit for the same voltage, and provided with cable connection in and out, was supplied for the control of the system at a distant point.

Other switchgear, by the same makers, for a system voltage at 3.3 kV. is provided, consisting of one 5-unit and one 3-unit switchboard supplied by power through a B.E.T. transformer from the 11,000-volt main switchboard. On account of the impedance of the step-down transformer, it was possible to use a switch having a short circuit rating of 50 MVA., this rating having also been proved in a short testing station. The transformer has primary kVA. 455, secondary 660, and a voltage ratio of 10500/470. It is provided with a tapping range of plus and minus 6 per cent. covered by a 6-step, 7-position, manually operated on-load tap-changing equipment.

Arranged for indoor service, the transformer has a conservator and cable boxes in view of the dust-laden atmosphere normally obtaining in cement works. It is a 12-phase connected machine, feeding a Nevelin glass twin-bulb rectifier unit. In this way the direct current supply is reduced to about 1 per cent. and wireless or telephone interference is avoided. Each glass bulb unit is capable of giving 500 amperes at 500 volts continuously with overloads of 25 per cent. for two hours, 50 per cent. for half an hour, and 100 per cent. for 15 seconds. The power factor and efficiency as measured on the site were : Power factor, 0·96 at full load dropping to 0·92 at quarter load ; Efficiency, 93·8 per cent. at full load dropping to 91 per cent. at quarter load.

The mill motors in this plant are of Crompton Parkinson manufacture ; they are of the auto-synchronous type rated at 250 h.p., 600 r.p.m., designed for running at 0·9 leading power factor, and each drives a cement mill through a reduction gear. The washmill motors are of the Crompton pedestal-bearing slip-ring type rated at 200 h.p., the stators being interchangeable with the stators of the synchronous induction motors. The stator control switches of these motors are also of the truck type. The majority of the direct current motors for the auxiliary drives are supplied from a 400 kW. twin-bulb mercury-arc rectifier.

At the works of the Associated Portland Cement Manufacturers, Ltd., at Sundon, near Luton, the supply enters through an outdoor sub-station at 20,000 volts and, by means of two 1,000 kVA. transformers, is stepped down to 3,000 volts, 3-phase, 50 cycles. The switchgear, of truck cubicle type of Crompton Parkinson manufacture, controls the outgoing circuits, while transformers housed in the works sub-station give the 500-volt, 3-phase, 50 cycle supply for the smaller motors. A unit of the truck switchboard also controls supply to the washmill sub-station in which a 4-panel truck-type Crompton Parkinson switchboard is installed to control two washmill motors and a 150 kVA. transformer is provided for supplying the smaller motors. A single-truck cubicle fed from the main truck-type switchboard controls an 800 h.p. induction motor driving the cement mill.

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